SLAC-PUB-7827
May 1998

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Submitted to *Physical Review D*

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Work supported by Department of Energy contract DE–AC03–76SF00515.

hep-ph/yymmnnn
SLAC-PUB-7827
May 11, 1998

Cornering gauge-mediated supersymmetry breaking with quasi-stable sleptons at the Tevatron

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Abstract

There are many theoretical reasons why heavy quasi-stable charged particles might exist. Pair production of such particles at the Tevatron can produce highly ionizing tracks (HITs) or fake muons. In gauge-mediated supersymmetry breaking, sparticle production can lead to events with a pair of quasi-stable sleptons, a significant fraction of which will have the same electric charge. Depending on the production mechanism and the decay chain, they may also be accompanied by additional energetic leptons. We study the relative importance of the resulting signals for the Tevatron Run II. The relative fraction of same-sign tracks to other background-free signals is an important diagnostic tool in gauge-mediated supersymmetry breaking that may provide information about mass splittings, $\tan\beta$ and the number of messengers communicating supersymmetry breaking.

[†]Work supported by the Department of Energy under contract DE-AC03-76SF00515.

Low-energy supersymmetry has emerged as an excellent candidate solution to the hierarchy problem associated with the existence of the small ratio $M_W/M_{\rm Planck}$ in the Standard Model. However, the existence of squarks and sleptons in the Minimal Supersymmetric Standard Model (MSSM) seems to lead to another potential difficulty: the supersymmetric flavor problem. If the soft supersymmetry-breaking mass parameters for squarks, sleptons, and gauginos do not greatly exceed 1 TeV, as suggested by a solution to the hierarchy problem, then arbitrary mixing angles associated with these mass terms can induce unacceptably large flavor-changing effects in low-energy processes like $\mu \to e\gamma$, $K^0 \leftrightarrow \overline{K}^0$, $b \to s\gamma$, etc. Conversely, the required absence of such flavor violation can be viewed as a strong constraint, and therefore a powerful clue, regarding the nature of supersymmetry breaking.

Historically, the more popular approach has been to assume that supersymmetry-breaking effects have their origin in a "hidden sector", and are then communicated only (or dominantly) by Planck-suppressed effects to the fields of the MSSM. However, within this framework, the absence of low-energy flavor-changing neutral currents really depends on further implicit assumptions, since *a priori* it is just as likely to mediate supersymmetry breaking to the MSSM with flavor-violating Planck-suppressed operators as with flavor-blind ones. One may impose an approximate flavor symmetry on the relevant terms in the lagrangian, but it is rather controversial whether this can be well-motivated theoretically by deeper principles.

An alternative hypothesis [1, 2] is that the ordinary gauge interaction $SU(3)_C \times SU(2)_L \times U(1)_Y$ are responsible for communicating supersymmetry breaking effects to the MSSM fields. In these gauge-mediated supersymmetry-breaking (GMSB) models, the absence of large flavor-violating effects in low-energy physics is a natural consequence of the flavor-blindness of the Standard Model gauge interactions. The supersymmetry-breaking sector of the theory couples to some new "messenger" quark and lepton superfields with vector-like $SU(3)_C \times SU(2)_L \times U(1)_Y$ interactions. For example, suppose that the messenger quarks and leptons come in $N_{\rm mess}$ copies of the $\mathbf{5} + \overline{\mathbf{5}}$ representation of the global $SU(5)$ symmetry which includes $SU(3)_C \times SU(2)_L \times U(1)_Y$. Because of the effects of dynamical supersymmetry breaking, there is a small splitting among the messenger fermion and scalar masses. In the simplest types of models with only one F-term supersymmetry breaking order parameter, this can be parameterized as follows. For each messenger fermion with mass m_{ψ_i}, the messenger scalar partner masses are given by $m_{\psi_i}\sqrt{1 \pm \Lambda/m_{\psi_i}}$, where Λ is a constant mass scale which is the same for all of the messenger supermultiplets. In order for the messenger scalars not to develop color- or charge-breaking

vacuum expectation values, it is necessary that $\Lambda < m_{\psi_i}$ for each messenger supermultiplet. It is usual to assume that the messenger particles are roughly degenerate, with masses all of order $M_{\rm mess}$, so that Λ can be treated as a perturbation with respect to $M_{\rm mess} \approx m_{\psi_i}$.

With these assumptions, the MSSM gaugino and scalar soft supersymmetry-breaking masses can be easily calculated at leading order in an expansion in $\Lambda/M_{\rm mess}$ [2]. Gaugino masses are communicated from the messenger sector to the MSSM at one loop

$$M_a = N_{\rm mess}\Lambda \frac{\alpha_a}{4\pi} \qquad\qquad (a = 1, 2, 3), \tag{1}$$

and are proportional to the corresponding squared gauge couplings. Squark, slepton, and Higgs boson squared masses arise at two loops and are given by

$$m_\phi^2 = 2N_{\rm mess}\Lambda^2 \sum_{a=1}^{3} \left(\frac{\alpha_a}{4\pi}\right)^2 C_a^\phi \tag{2}$$

where C_3^ϕ is equal to 4/3 for each squark and 0 for other scalars; C_2^ϕ is equal to 3/4 for weak isodoublet scalars and 0 for weak isosinglets, and $C_1^\phi = 3Y_\phi^2/5$ for each scalar of weak hypercharge Y_ϕ with α_1 in a GUT normalization. Equations (1) and (2) are subject to corrections in $\Lambda/M_{\rm mess}$ which turn out to be usually quite small [3] and will be neglected in the following. The sparticle spectrum can now be computed by using renormalization group equations to run the masses eqs. (1) and (2) and other couplings from the scale $M_{\rm mess}$ down to the electroweak scale [4, 5, 6]. This class of models is therefore highly predictive, with input parameters Λ, $M_{\rm mess}$, $N_{\rm mess}$, $\tan\beta$, and $\mathrm{sgn}(\mu)$, and the phenomenology is quite distinctive [5]-[15].

The prediction of a goldstino/gravitino ($\widetilde{G}$) [16, 7] as the lightest supersymmetric particle (LSP) is another general feature of GMSB models. In terms of the parameters Λ and $M_{\rm mess}$ above, the supersymmetry-breaking order parameter is $\langle F \rangle = C\Lambda M_{\rm mess}$, where C is a dimensionless constant which can be of order unity (for "direct" gauge-mediation models), or much larger than 1 (for "indirect" gauge-mediation models), but not much less than 1. Each of the MSSM sparticles can decay into final states including the goldstino/gravitino $\widetilde{G}$, with rates proportional to $1/\langle F \rangle^2$. However, the decays of MSSM sparticles to the goldstino will typically be dominated by other kinematically-allowed decays, except in the case of the next-to-lightest supersymmetric particle (NLSP). If R-parity is conserved, as motivated by the absence of rapid proton decay, then the NLSP can only decay to its Standard Model partner(s) and the goldstino/gravitino. Whether the NLSP can decay quickly enough to be visible within a collider detector depends on the identity and mass of the NLSP, and on the goldstino decay constant $\langle F \rangle$. If $\langle F \rangle$ is less than a few thousand TeV, then one can hope to observe decays to the gold-

stino within a typical collider detector, with potentially spectacular consequences. Conversely, if $\langle F \rangle \gg 10^3$ TeV, then all decays involving $\widetilde{G}$ will occur far outside the detector.

In GMSB models of the type discussed above, the NLSP is generally either the lightest neutralino ($\widetilde{N}_1$) or a charged slepton, depending on the model parameters. In this paper, we will concentrate on the latter case. The three lightest sleptons generally consist of the nearly unmixed and degenerate right-handed selectron and smuon $\widetilde{e}_R$ and $\widetilde{\mu}_R$, and a mixed stau mass eigenstate $\widetilde{\tau}_1$. The reason for this is that each of the slepton (mass)^2 matrices contains an off-diagonal term $-\mu m_\ell \tan\beta$ where m_ℓ is the mass of the corresponding lepton. This provides for slepton mixing and lowers the corresponding slepton mass eigenvalue. In the case of the selectron and smuon, this effect is quite small, only reducing the mass of the smuon by at most a few tens of MeV, and the mass of the selectron by much less. Therefore we will simply neglect smuon and selectron mixing and treat them as degenerate, unmixed states. However, because of the hierarchy $m_\tau \gg m_\mu$, the stau mixing is not negligible unless $\tan\beta$ is close to 1, so that

$$m_{\widetilde{\tau}_1} < m_{\widetilde{e}_R} \simeq m_{\widetilde{\mu}_R}. \tag{3}$$

Therefore, it is useful to distinguish between two qualitatively distinct scenarios, depending on whether or not the right-handed selectrons and smuons ($\widetilde{e}_R$ and $\widetilde{\mu}_R$) can have kinematically allowed decays into the lightest stau $\widetilde{\tau}_1$. If the mass difference $m_{\widetilde{\ell}_R} - m_{\widetilde{\tau}_1}$ exceeds about 1.8 GeV, then one can have three-body decays

$$\widetilde{\ell}_R^- \to \ell^- \tau^\pm \widetilde{\tau}_1^\mp \tag{4}$$

for $\ell = e$ or μ, and similarly for $\widetilde{\ell}_R^+$. In that case we have a "stau NLSP scenario", in which all supersymmetric decay chains end up in $\widetilde{\tau}_1$, with a subsequent (possibly very slow) decay

$$\widetilde{\tau}_1 \to \tau \widetilde{G}. \tag{5}$$

Conversely, if $\widetilde{\ell}_R$ and $\widetilde{\tau}_1$ are degenerate in mass to within less than 1.8 GeV, then the aforementioned three-body decays are not kinematically allowed. In this "slepton co-NLSP" scenario, the three sleptons $\widetilde{e}_R$, $\widetilde{\mu}_R$ and $\widetilde{\tau}_1$ each act *effectively* as the NLSP despite eq. (3), in the sense that they only have kinematically allowed decays into the goldstino.* The lightest stau will decay according to eq. (5), while the lightest selectron and smuon decay according to $\widetilde{e}_R \to e\widetilde{G}$ and $\widetilde{\mu}_R \to \mu\widetilde{G}$ respectively.

*An exception occurs if $|m_{\widetilde{N}_1} - m_{\widetilde{\tau}_1}| < m_\tau$ and $m_{\widetilde{\ell}_R} > m_{\widetilde{N}_1}$, which corresponds to a neutralino-stau co-NLSP scenario.

In this paper, we will consider slepton co-NLSP models and stau NLSP models, with the subsequent decays to the goldstino/gravitino $\widetilde{G}$ assumed to be very slow, so that they always occur outside the detector. (If instead those decays occur promptly, or with a macroscopic decay length but within the detector, then the signals from additional hard leptons and/or decay kinks or impact parameters will be even more spectacular.) The quasi-stable sleptons arising from supersymmetric events can then manifest themselves in different ways in a detector, depending on how fast they are [17, 18, 14]. The relevant kinematic variable is $\beta\gamma = \left(E^2/m_{\widetilde{\ell}}^2 - 1\right)^{1/2}$ where E is the relativistic energy of the slepton in the lab frame. For $\beta\gamma \gtrsim 1$ or so, the ionization rate $-dE/dx$ of the slepton as it moves through the detector material is minimal, and the fast slepton penetrates the detector, mimicking a "muon". Slow sleptons with $\beta\gamma \lesssim 1$ have a greater-than-minimum ionization rate as they move through the detector material. The ionization rate increases sharply as $\beta\gamma$ decreases, so that for $\beta\gamma < 0.85$ or 0.9 the resulting Highly Ionizing Track (HIT) can be readily distinguished from that of a muon [17, 18, 5, 14].

At the Tevatron Run II, the most important sparticle production mechanisms are then typically slepton production,

$$p\overline{p} \to \widetilde{e}_R^+\widetilde{e}_R^-,\ \widetilde{\mu}_R^+\widetilde{\mu}_R^-\ \text{ or }\ \widetilde{\tau}_1^+\widetilde{\tau}_1^- \tag{6}$$

and/or chargino/neutralino production,

$$p\overline{p} \ \ \to \ \ \widetilde{C}_1^+\widetilde{C}_1^-\ \text{ or }\ \widetilde{C}_1^\pm\widetilde{N}_2. \tag{7}$$

Of course, other processes can contribute small amounts to the signal. Production of heavier slepton pairs ($\widetilde{\nu}\widetilde{\nu}$, $\widetilde{\nu}\widetilde{\ell}_L^\pm$, $\widetilde{\ell}_L^+\widetilde{\ell}_L^-$) is generally less important than eq. (6), but may still be observable. Other chargino and neutralino combinations ($\widetilde{C}_i^+\widetilde{C}_j^-$, $\widetilde{C}_i^\pm\widetilde{N}_j$, and $\widetilde{N}_i\widetilde{N}_j$) might give significant contributions, especially if the higgsino contents of the $\widetilde{N}_1$, $\widetilde{N}_2$ and $\widetilde{C}_1$ are not negligible. Production of gluinos and squarks is generally quite negligible within the class of GMSB models we consider, because they tend to be relatively heavy. In the simulations described below we simply include all contributions to sparticle pair production.

Each supersymmetric event leads to a pair of quasi-stable sleptons which may be identified as either a "muon" or a HIT. In addition, a high percentage of these events can actually have quasi-stable sleptons with the same charge in the final state. For example, in the case of $\widetilde{C}_1^\pm\widetilde{N}_2$ production, the $\widetilde{N}_2$ will decay equally to sleptons with either charge. Events with $\widetilde{C}_1^+\widetilde{C}_1^-$ (or $\widetilde{\nu}\widetilde{\nu}$, $\widetilde{\nu}\widetilde{\ell}_L^\pm$, $\widetilde{\ell}_L^+\widetilde{\ell}_L^-$) production will lead to roughly equal numbers of like- and opposite-charge slepton NLSPs whenever any part of the decay chains involves a real or virtual neutralino, because the neutralinos are Majorana particles and do not know about electric charge. In

the slepton co-NLSP scenario, $\widetilde{e}_R^+\widetilde{e}_R^-$, $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$, and $\widetilde{\tau}_1^+\widetilde{\tau}_1^-$ production always leads to opposite-charge sleptons. However, in the stau-NLSP scenario, $\widetilde{e}_R^+\widetilde{e}_R^-$ and $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$ production usually leads to roughly equal numbers of same-sign and opposite-sign staus in the final state. This is because the three-body decays $\widetilde{\ell}_R^- \to \ell^-\tau^\pm\widetilde{\tau}_1^\mp$ go through a virtual neutralino, so that the charge of the $\widetilde{\tau}_1$ is nearly uncorrelated with the charge of its parent $\widetilde{\ell}_R$ when $m_{\widetilde{N}_1}$ is not much larger than $m_{\widetilde{\ell}_R}$. As $m_{\widetilde{N}_1}/m_{\widetilde{\ell}_R}$ increases, the branching fraction for the "slepton charge-flipping" decays $\widetilde{\ell}_R^- \to \ell^-\tau^-\widetilde{\tau}_1^+$ increases at the expense of the "slepton charge-preserving" decays $\widetilde{\ell}_R^- \to \ell^-\tau^+\widetilde{\tau}_1^-$ [13]. However, for reasonable values of $m_{\widetilde{N}_1}/m_{\widetilde{\ell}_R}$ found in GMSB models with a $\widetilde{\tau}_1$ NLSP as studied here, the number of events from $\widetilde{e}_R^+\widetilde{e}_R^-$ and $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$ production with like-sign staus will be comparable to (albeit smaller than) the number with opposite sign staus. If, as is often the case in models, the mass difference $m_{\widetilde{\ell}_R} - m_{\widetilde{\tau}_1}$ is not too large, then the ℓ and the τ produced in the decay will be very soft and will fail to pass cuts for lepton identification.

In order to define our signals, we require that events pass at least one of the following two triggers.[†] First, events are triggered if at least one quasi-stable slepton has $|\eta| < 0.6$ and $\beta\gamma > 0.4$. The pseudorapidity requirement corresponds to the highly-shielded central region of the CDF detector in order to cut down on backgrounds. The lower limit on $\beta\gamma$ ensures that the slepton will penetrate the calorimeters. Second, events are triggered with at least one fast quasi-stable slepton which mimics a high-p_T central muon. This requires the trigger slepton to satisfy $\beta\gamma > 0.85$ and $|\eta| < 1.0$. The lower limit on $\beta\gamma$ is to ensure that the fast slepton will have a reasonable probability of penetrating the detector within a narrow time window in order to satisfy identification requirements for a muon. (Note that if a slepton with mass greater than 90 GeV satisfies these requirements, it will necessarily have $p_T > 50$ GeV in the case of the first trigger and $p_T > 30$ GeV in the case of the second trigger, so we do not require a separate p_T cut.) We find that in most of the cases studied below, the percentage of supersymmetric events which pass at least one of these two trigger requirements is quite high, typically between 70% and 85%.

After an event comes in on trigger, we identify particles according to the following criteria:

- A quasi-stable slepton is identified as a HIT if it has $|\eta| < 1.0$ and $0.4 < \beta\gamma < 0.85$ and $p_T > 30$ GeV.
- A quasi-stable slepton is identified as a "muon" if it fails the HIT requirement and satisfies $|\eta| < 1.7$ and $\beta\gamma > 0.85$.

[†]We are grateful to D. Stuart for explaining the trigger and HIT identification requirements relevant for CDF in Run II.

- A real electron or muon must satisfy $|\eta| < 1.7$ and $p_T > 12$ GeV.
- A jet must satisfy $|\eta| < 3.0$ and $p_T > 15$ GeV.

In the case of a HIT, "muon" or a real lepton, we impose an isolation requirement that within a cone $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ there should be no other HIT, "muon" or lepton and that the total hadronic energy should not exceed 5 GeV.

Within this trigger sample, we now define the following signals:

1) HIT: Events with at least one isolated slepton identified as a HIT.

2) SS: A pair of *same-sign* fast sleptons each passing the "muon" cut above, with no other isolated leptons.

3) 3ℓ: Trilepton signal consisting of two fast sleptons which each pass the "muon" cut above, and exactly one additional isolated e or μ, and no jets.

4) $4\ell+$: Four or more isolated lepton candidates, including two fast sleptons which each pass the "muon" cut above.

In the trilepton signal case (3ℓ), we demand that no pair of oppositely charged muon candidates reconstructs to an invariant mass $m_Z \pm 10$ GeV in order to reduce the backgrounds from WZ production. (Here we use the invariant mass as reconstructed from the 3-momenta of the particles assuming they are essentially massless, which does not coincide with the true invariant mass since at least one of the pair is actually a massive slepton.) We also do not allow any jets in the event from initial state radiation or primary decay products. Such a jet veto avoids potentially large backgrounds from $t\bar{t}$ production. In the $4l+$ signal we require that it not be consistent with ZZ production. The invariant mass cuts to accomplish this are the same as for the $3l$ signal discussed above. We should also note that a significant fraction of the $4l+$ events will have 5 or 6 isolated leptons arising from gaugino cascade decays. Since the "muons" in these events always have $p_T > 50$ GeV for $m_{\tilde{\ell}} > 90$ GeV, there should be essentially no background after cuts for all of the signals proposed above, except the $3l$ signal whose background can be rendered insignificant with sufficiently hard p_T cuts on the "muons."

Let us now study the relative importance of the signals defined above for $\overline{p}p$ collisions at $\sqrt{s} = 2$ TeV, as is relevant for the Tevatron Run II scheduled to begin in 2000. We will examine representative models in the parameterization of eqs. (1)-(2). Our collider simulations

have been performed using ISAJET [19]. A first quantitative study with somewhat different emphasis and different definitions of signals and cuts has been carried out in ref. [14].

We first consider a one-parameter family of slepton co-NLSP models with $N_{\rm mess} = 3$, $\tan\beta = 3$, $\mu > 0$ (in the sign convention of ref. [20]) and varying Λ with $M_{\rm mess} = 3\Lambda$. (The factor of 3 here is rather arbitrary, but the sparticle spectrum depends on $M_{\rm mess}$ only logarithmically anyway.) Since the LEP2 collaborations [15] should be able to rule out slepton masses up to at least 90 GeV in the scenarios we consider, we take Λ to vary over a range 27 TeV $< \Lambda <$ 80 TeV which corresponds to 90 GeV $< m_{\widetilde{\tau}_1} <$ 250 GeV. In this family of models, the mass differences $m_{\widetilde{e}_R} - m_{\widetilde{\tau}_1}$ and $m_{\widetilde{\mu}_R} - m_{\widetilde{\tau}_1}$ are always positive and less than 1 GeV, so that the three-body decays in eq. (4) are not open, and $\widetilde{e}_R$, $\widetilde{\mu}_R$, and $\widetilde{\tau}_1$ are effectively co-NLSPs. We note that in the lower mass regions ($m_{\widetilde{\tau}_1} \lesssim 150\,{\rm GeV}$) the chargino and neutralino production rate constitutes the largest source of supersymmetry events at the Tevatron. At higher mass regions ($m_{\widetilde{\tau}_1} \gtrsim 150\,{\rm GeV}$) it is slepton production which dominates. In Fig. 1 we show the four signal cross-sections and their total after the trigger, identification and isolation cuts described above. Using a discovery criterion of 7 total signal events, we find that a discovery should be possible for $m_{\widetilde{\tau}_1} <$(140, 185, 225) GeV in these models for an integrated luminosity of (2, 10, 30) fb^{-1}. These $\widetilde{\tau}_1$ mass limits correspond to limits on the lightest chargino mass, $m_{\widetilde{C}_1} < (320, 430, 540)$ GeV in these particular models, but it is important to note that slepton production is the dominant contribution to the signal for larger masses. The HIT signal is clearly the largest single one over the entire range, but the $4\ell+$ signal can be a significant component, and for smaller values of $m_{\widetilde{\tau}_1}$ the 3ℓ and SS signals can also be observed with sufficient integrated luminosity. However, for larger sparticle masses, the discovery signal comes almost entirely from the HIT signal.

Next we consider a similar one-parameter family of models with all other parameters as before, but now with $\tan\beta = 10$. Because of the larger mixing in the stau (mass)^2 matrix, the mass differences $m_{\widetilde{e}_R} - m_{\widetilde{\tau}_1}$ and $m_{\widetilde{\mu}_R} - m_{\widetilde{\tau}_1}$ are now always greater than 3 GeV for $m_{\widetilde{\tau}_1} < 250$ GeV, so that the three-body decays $\widetilde{e}_R \to e\tau\widetilde{\tau}_1$ and $\widetilde{\mu}_R \to \mu\tau\widetilde{\tau}_1$ are kinematically allowed. These models are therefore examples of the stau NLSP scenario. The corresponding signal cross-sections are shown in Fig. 2. Again, the HIT signal is the largest one, but the SS signal is quite significant over the entire range, amounting to about 20 to 35% of the total signal events. Most of these SS events arise from direct production of $\widetilde{e}_R^+\widetilde{e}_R^-$ or $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$ with subsequent three-body decays. The existence of the SS signal allows the discovery reach in $m_{\widetilde{\tau}_1}$ to be slightly higher (about 10 GeV) in these stau NLSP models than in the analogous slepton co-NLSP models in Fig. 1. (In slepton co-NLSP models, direct $\widetilde{e}_R^+\widetilde{e}_R^-$, $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$, and $\widetilde{\tau}_1^+\widetilde{\tau}_1^-$ production can

never lead to a SS signal.) The $4\ell+$ signal can also be important for smaller values of $m_{\widetilde{\tau}_1}$.

In Fig. 3 we show the same signals but now with varying $\tan\beta$, with $N_{\rm mess} = 3$, $\mu > 0$, and $\Lambda = M_{\rm mess}/3$ chosen so that $m_{\widetilde{\tau}_1}$ is fixed at 110 GeV. The mass difference between $\widetilde{e}_R$ (or equivalently, $\widetilde{\mu}_R$) and $\widetilde{\tau}_1$ is followed on the upper horizontal axis. For $\tan\beta \gtrsim 6.6$ the three-body decays for $\widetilde{e}_R$ and $\widetilde{\mu}_R$ open up, and the same-sign "muon" signal becomes large. [‡] For very large values of $\tan\beta$, the masses of the $\widetilde{e}_R$ and $\widetilde{\mu}_R$ must be much higher than the lighter stau mass, which is fixed at 110 GeV for the figure. Therefore, the largest source for SS dimuons – $\widetilde{e}_R^-\widetilde{e}_R^+$ and $\widetilde{\mu}_R^-\widetilde{\mu}_R^+$ – gets quite small again. Also, the additional leptons in the three-body decays become energetic enough to pass the lepton cuts, so these events contribute to the 3ℓ and $4\ell+$ signals rather than the SS signal. At the very largest values of $\tan\beta$, $\widetilde{\tau}_1^+\widetilde{\tau}_1^-$ becomes by far the dominant discovery process, leading to essentially only a HIT signal. Fig. 3 illustrates that the ratio of HITs to SS dimuons is an interesting probe of $\tan\beta$ in gauge mediated models.

So far we have considered models with fixed $N_{\rm mess} = 3$. It is also interesting to consider how the signals change if $N_{\rm mess}$ is varied,[§] since this has the effect of changing the overall ratios of the slepton masses to the gaugino mass parameters. In Fig. 4 we show the signals as a function of $N_{\rm mess}$, with $\tan\beta = 3$, $\mu > 0$, and $\Lambda = M_{\rm mess}/3$ chosen in such a way that $m_{\widetilde{\tau}_1}$ is held fixed at 110 GeV. (The lower endpoint of the graph is determined by the fact that for $N_{\rm mess} \lesssim 2.2$, one finds $m_{\widetilde{N}_1} < m_{\widetilde{e}_R}, m_{\widetilde{\mu}_R}$ in these models, so that we are no longer in the slepton co-NLSP scenario. For smaller $N_{\rm mess}$, the NLSP will be a neutralino, leading to missing energy signals if the decays to the goldstino/gravitino $\widetilde{G}$ take place outside the detector.) For all values of $N_{\rm mess}$, the HIT signal is the largest component of the total. For the lower values of $N_{\rm mess}$, the charginos and neutralinos are sufficiently light that $\widetilde{C}_1^+\widetilde{C}_1^-$ and $\widetilde{C}_1^\pm\widetilde{N}_2$ production dominate. As $N_{\rm mess}$ increases, the $\widetilde{C}_1$ and $\widetilde{N}_2$ decays tend to yield more additional leptons, so that the $4\ell+$ signal quickly overtakes the SS signal. For the largest values of $N_{\rm mess}$, slepton production dominates and there is essentially no SS signal at all.

The situation is again quite different for stau NLSP models, as illustrated in Fig. 5. Here we have chosen $\tan\beta = 10$ and all other parameters as in Fig. 4. This ensures that the mass differences $m_{\widetilde{e}_R} - m_{\widetilde{\tau}_1}$ and $m_{\widetilde{\mu}_R} - m_{\widetilde{\tau}_1}$ are greater than 3 GeV, so that the three-body decays of $\widetilde{e}_R$ and $\widetilde{\mu}_R$ are open. This in turn guarantees that over the whole range of $N_{\rm mess}$ shown, the SS signal

[‡] There is a small range of $\tan\beta$ near the boundary between the two scenarios for which the mass differences $m_{\widetilde{\ell}_R} - m_\ell - m_\tau - m_{\widetilde{\tau}_1}$ are positive but small, so that the three-body decays can have a macroscopic decay length [13]. We will not explore that interesting possibility in the following.

[§] In the simplest GMSB models, $N_{\rm mess}$ is taken to be an integer, but one can easily imagine more general frameworks of models in which the effective value for $N_{\rm mess}$ is not so restricted.

is a significant component of the total. With enough integrated luminosity it may be possible to extract information about the number of messengers by measuring the superpartner masses and comparing the $3l$ and $4l+$ rates. Even more information can be obtained by measuring the proportion of 4, 5, and 6 lepton events in the latter sample. However, for any given model these ratios are quite strongly dependent on the choice of lepton p_T cuts which in turn depend on experimental realities that are difficult to anticipate, so we will not analyze them here.

It is useful to remark on the proportion of $\widetilde{e}_R^+\widetilde{e}_R^-$ and $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$ events which lead to same-sign staus in the final state. For example, in Fig. 5, the ratio of "slepton charge-flipping" decays $\widetilde{\ell}_R^- \to \ell^-\tau^-\widetilde{\tau}_1^+$ to "slepton charge-preserving" decays $\widetilde{\ell}_R^- \to \ell^-\tau^+\widetilde{\tau}_1^-$ increases monotonically from 1 to about 4.6 as $N_{\rm mess}$ increases from the minimum value of 2.1 to 10. This increase is attributable to the corresponding rise in the ratio $m_{\widetilde{N}_1}/m_{\widetilde{\ell}_R}$, since off-shell neutralinos in the three-body decays eq. (4) favor the slepton charge-flipping channel, while nearly on-shell neutralinos do not distinguish between the two channels [13]. This means that for $N_{\rm mess} = 2.1$, nearly 50% of the $\widetilde{e}_R^+\widetilde{e}_R^-$ and $\widetilde{\mu}_R^+\widetilde{\mu}_R^-$ events will have same-sign staus in the final state, while for $N_{\rm mess} = 10$, the fraction with same-sign staus decreases to about 27%. (Note that for smaller values of $N_{\rm mess}$, the deviation of this fraction from 50% is much less; for example, in the models shown in Fig. 2, it never gets below about 46%.) In addition, there is a large direct production of $\widetilde{\tau}_1^+\widetilde{\tau}_1^-$ which further dilutes the ratio of same-sign stau final states.

It should also be noted that chargino and neutralino production will lead to some same-sign events with branching fractions that are functions of the model parameters. Certainly, all $\widetilde{C}_1^\pm\widetilde{N}_2$ events will lead to same-sign quasi-stable sleptons in the final state, simply because the decay of the neutral Majorana particle $\widetilde{N}_2$ must be democratic between different charge channels. In most of the models studied above, the production cross-section for $\widetilde{C}_1^+\widetilde{C}_1^-$ is larger than for $\widetilde{C}_1^\pm\widetilde{N}_2$, but it can also lead to same-sign sleptons in the final state whenever any part of the decay chain goes through a real or virtual neutralino. Only a small fraction of these events will be counted in the SS signal as defined above which excludes events with HITs or additional leptons. However, it is important to keep in mind that a sizeable fraction of all the signals will have same-sign sleptons which can be an important observable. Thus one can, for example, measure the charges of the two tracks with the highest p_T which qualify as a muon candidate or a HIT, and then compare the ratio of same-sign to opposite-sign charges. This observable can be defined for each of the signals given above, and should give an important confirmation of the slepton interpretation of these events, as well as some information about the model parameters.

In our study the number of SS events compared to HITs depends critically on detector performance. For example, in the limit that detectors cannot distinguish between muons and heavy charged particles at *any* $\beta\gamma$, the HITs signal will of course go to zero and the other signals will rise. Ratios between SS, $3l$ and $4l+$ signals will then have very similar dependences to those found above, and information about the number of messengers and $\tan\beta$ can be studied in a similar fashion. In other words, the qualitative features do not disappear with variations in the detector parameters. In our study we have attempted to mimic detector performance similar to that expected at CDF and D0.

In conclusion, quasi-stable heavy charged particles are present in many extensions beyond the Standard Model. As expected the reach in supersymmetry masses is very high in this scenario since highly-ionizing "cannonballs" in the detector are hard to miss. Mass limits well in excess of the capabilities at LEPII are possible. Indeed, the Tevatron Run II can probe much of the parameter space where GMSB sparticles might be expected to appear, based on a solution to the hierarchy problem without significant fine-tuning [21]. However, only a detailed study of relative rates of new physics final states along the lines of those suggested above will enable a self-consistent picture to be formed of gauge-mediated supersymmetry at the Tevatron.

Acknowledgments: We are grateful to H. Baer and D. Stuart for useful conversations. The work of SPM was supported in part by the US Department of Energy.

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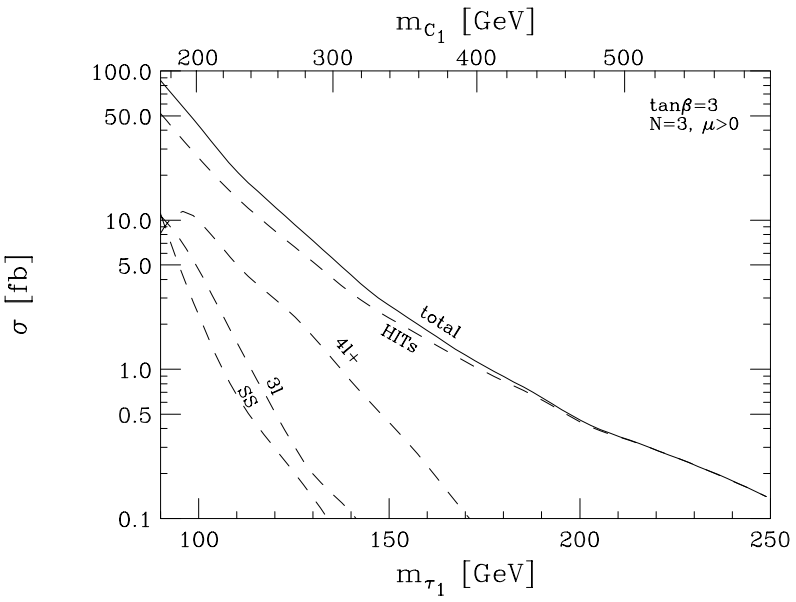

Figure 1: Cross-sections in fb for producing various final states from sparticle pair-production in $p\overline{p}$ collisions at $\sqrt{s} = 2$ TeV. The dashed lines are rates for events with at least one slepton identified as a highly ionizing track (HITs); four or more leptons including one or more fast sleptons masquerading as "muons" ($4\ell+$); trileptons including one or more "muons" (3ℓ); and same-sign "muons" with no other isolated leptons (SS). The results shown are for slepton co-NLSP GMSB models with varying $\Lambda = M_{\rm mess}/3$, and fixed $N_{\rm mess} = 3$, $\tan\beta = 3$, and $\mu > 0$. The solid line is the sum of the four signals.

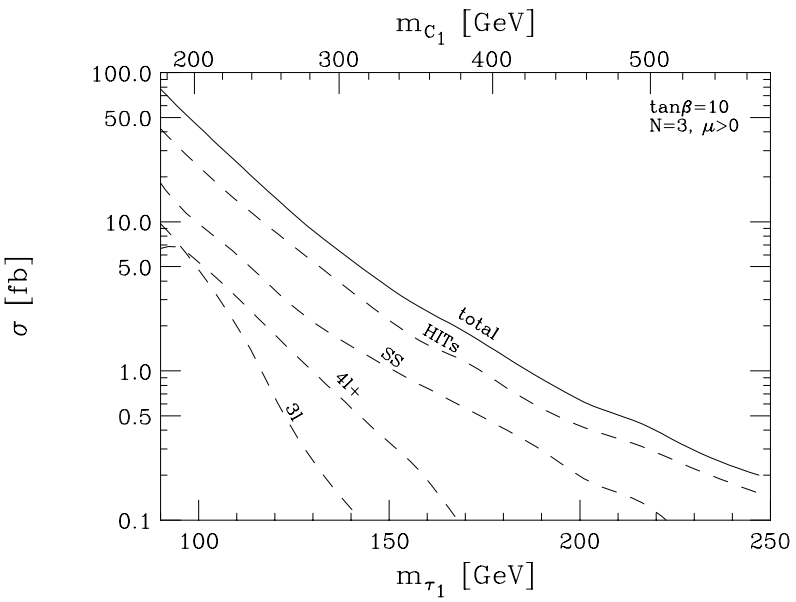

Figure 2: As in Figure 1, but for stau NLSP models with $\tan\beta = 10$. Note that the component of the signal due to same-sign "muons" is much more significant in this case.

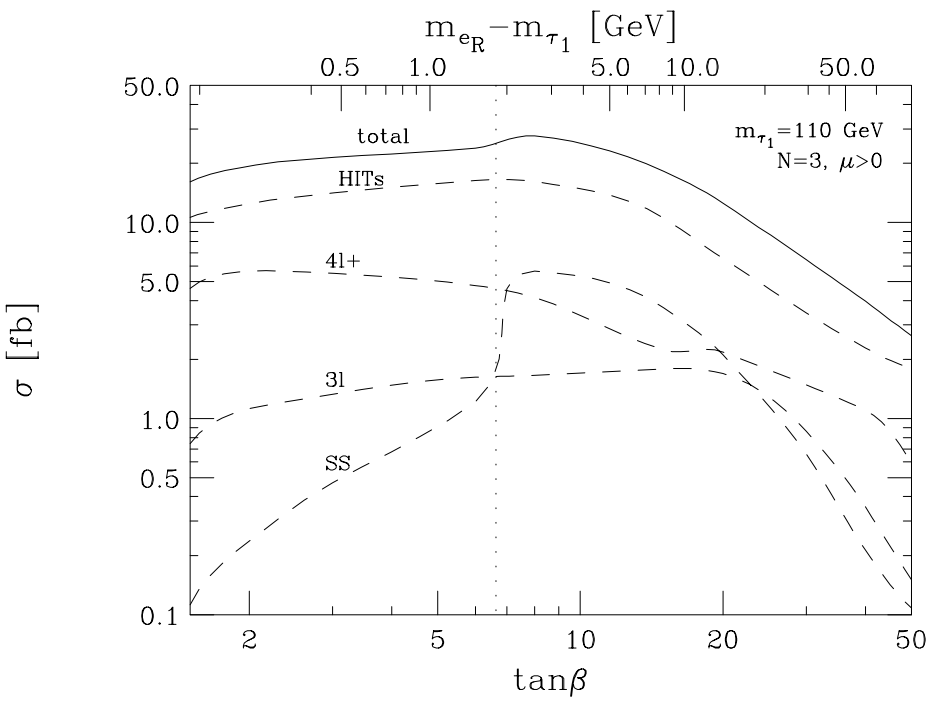

Figure 3: Cross-sections in fb for producing various final states from sparticle pair-production in $p\overline{p}$ collisions at $\sqrt{s} = 2$ TeV, labelled as in Figures 1 and 2. The results shown are for GMSB models with varying $\tan\beta$, and with $\Lambda = M_{\rm mess}/3$ chosen so that $m_{\tilde{\tau}_1}$ is fixed at 110 GeV, with $N_{\rm mess} = 3$, and $\mu > 0$. The dotted vertical line is the nominal boundary between the slepton co-NLSP scenario (on the left) and the stau NLSP scenario (on the right).

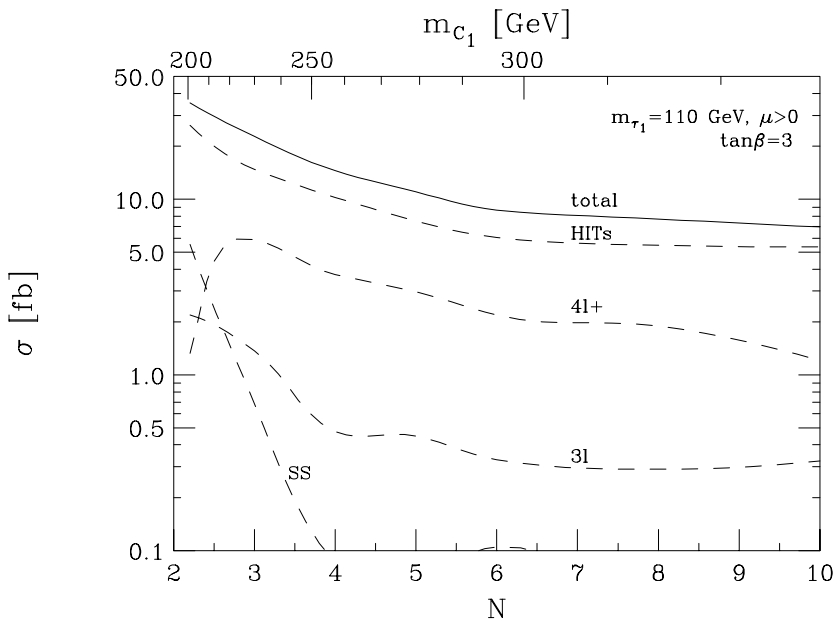

Figure 4: As in Figure 1, but for slepton co-NLSP models with the mass of $\widetilde{\tau}_1$ fixed at 110 GeV, $\tan\beta = 3$, and varying $N_{\rm mess}$.

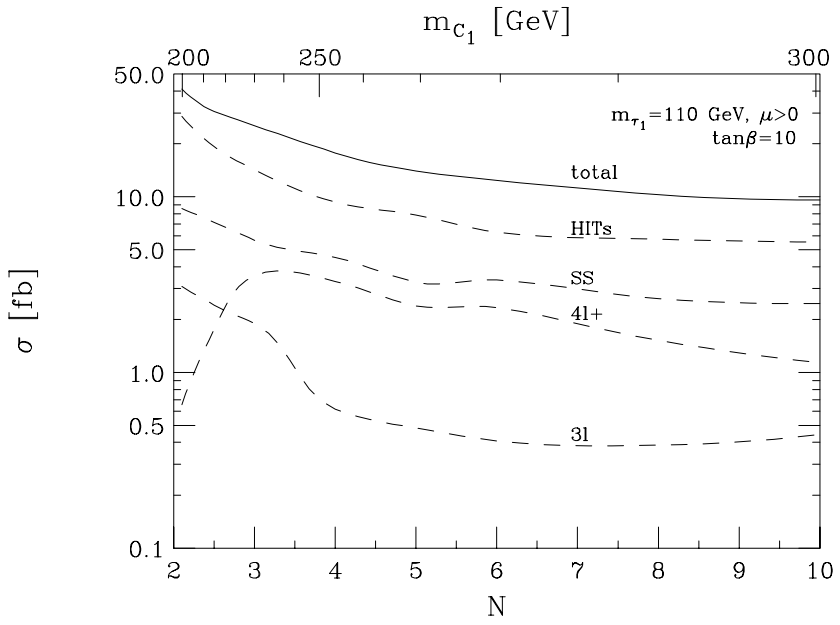

Figure 5: As in Figure 2, but for stau NLSP models with the mass of $\widetilde{\tau}_1$ fixed at 110 GeV, $\tan\beta = 10$, and varying $N_{\rm mess}$.